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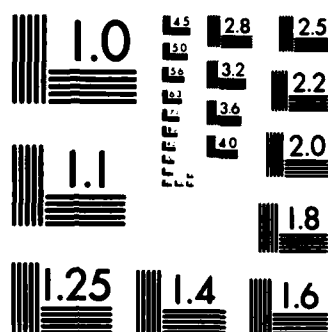FILMED

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Discontinuous silicon carbide/aluminum alloy (SiC/Al) metal matrix composites (MMC's) have exhibited improved physical and mechanical properties as compared to the properties of the wrought matrix alloy. These improved properties include high specific modulus, high creep strength, high fatigue resistance, low thermal expansion, and good thermal stability. The SiC/Al composites can be worked using standard metallurgical processing and hence they are inexpensive to produce compared to other MMC systems. The tensile ductility and fracture properties of the composite reported to date, however, are less than those of the wrought alloy. The tensile ductility has been improved by control of process parameters, but relatively little improvement in fracture toughness or notch sensitivity has been achieved.

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19. ABSTRACT (Continued)

Although the composite materials show limited gross ductility, their fracture behavior exhibits many of the characteristics of ductile fracture. The results show that the crack tip opening displacement, δ_t, is a linear function of the notch root radius and that the apparent fracture toughness, $K_{Ic}(\rho)$, can be accurately described by a two parameter function of the notch root radius, ρ:

$$K_{Ic}(\rho) = K_{Ic}(1 + \rho/2\ell)^{1.5} / (1 + \rho/\ell) \tag{1}$$

where K_{Ic} is the plane strain fracture toughness and ℓ is a numerical parameter related to a characteristic distance ahead of the crack tip.

The use of Eq. (1) has the very practical advantage of providing a method of extracting K_{Ic} from measurements on samples with finite root radii. Since it is a two parameter relationship, two specimens with different root radii provide sufficient information to extract K_{Ic} from non-precracked tests.

CONTENTS

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TOUGHNESS OF SILICON CARBIDE/ALUMINUM

METAL MATRIX COMPOSITES

INTRODUCTION

Discontinuous silicon carbide-aluminum (SiC/Al) metal matrix composites (MMC's) have been the subject of a number of investigations during the past few years. These studies have shown that this composite system develops a unique combination of desirable physical and mechanical properties such as high specific modulus and strength, high creep strength, high fatigue resistance, low coefficient of thermal expansion, and good thermal stability.[1-8] The composite also has the ability to be metal worked using standard metallurgical processing and is inexpensive to produce relative to other MMC systems. The tensile ductility and fracture properties which are obtained in the composite are, however, less than desirable.[1,9-14]

Although significant improvements have been made in increasing the tensile ductility by control of processing parameters during fabrication, relatively little improvement in the fracture toughness has been achieved and, indeed methods to measure the toughness in this material have not been standardized. This situation is due in part to the difficulty in fatigue precracking the toughness specimens, especially when the specimen thickness exceeds ~ 6mm. This difficulty is caused by a high resistance to fatigue crack initiation in the composite[6,7] and rapid crack propagation at low stress intensity excursion, ΔK.[15] Thus ASTM E399 and British methods to measure plane strain fracture toughness, K_{IC}, and to perform precracked Charpy tests have not always been followed. Instead, methods as close to standard as possible have been used whereby fatigue crack notches of ~ 0.5 μm to 1 μm notch root radius have been replaced by sharp spark machined or milled notches of 50 μm to 80 μm notch root radius. Therefore an understanding of the effect of notch acuity on the apparent fracture toughness is needed.

EXPERIMENTAL

The materials used in this study were 20 v/o SiC_w/6061 aluminum extruded tube, 20 v/o SiC_w/6061 aluminum plate, and 25 v/o SiC_p/6061 aluminum plate. The whisker composite was obtained from ARCO Metal, Silag Operations, Greer, SC, and the particulate composite from DWA Specialities, Inc., Chatsworth, CA. The SiC used in the whisker composites is a mixture of fine whiskers and particulate, with whisker content approximatley 80%. The whiskers are faulted β-silicon carbide with diameters ranging from 0.2 -1.0 μm and original lengths

up to 50 μm. The particulate SiC consists of irregularly shaped particles with a high percentage of flake like geometry. SiC is blended with -325 mesh commercially available inert gas atomized 6061 aluminum powders. Both composites are formed by cold compaction, followed by hot pressing at temperatures above the solidus of the matrix alloy to form "as-pressed" material.

The extruded tube material was taken from a 2cm wall thickness 32cm diameter back extruded cylinder produced from an "as-pressed" billet. The DWA plate materials was warm rolled to 6.35 mm thickness. The Arco plate material was first extruded to form a 12.5 mm x 12.6 cm flat extrusion which was then cross rolled in steps at elevated temperature to from a 6.35 mm thick plate. The processing breaks up the whiskers so that most of the whiskers in the ARCO composite as tested had L/D ratios between 2 and 5. Microstructures of the materials are shown in Fig. 1a and b. High magnification views of the whisker material revealed porosity in both the plate and the tube. Fig. 1a shows the morphology of this porosity. The frequency of observation was significantly greater in the plate material than in extruded tube suggesting that this porosity may have been introduced during hot working.

Plates were tested in the "as-received" condition which consisted of a nominal T6 aluminum alloy heat treatment. Specimens were cut from the cylinder in the R-L orientation and were heat treated at 500°C for 48 hours in a 25 millitorr vacuum and allowed to slow cool. This degassing heat treatment was followed by solution heat treatment at 527°C for one hour, cold water quenched, and then precipitation hardened at 177°C for 8 hours and air cooled. Tensile properties are listed in Table 1.

TABLE 1

Tensile Properties of SiC/Al Metal Matrix Composites

Material	Orientation	E(GPa)	σ_y(MPa)	σ_{uts}(MPa)	% Elong
20 v/$_o$ SiC$_w$/6061-T6	L	122	443	584	1.8
PLATE	T	91	409	480	3.8
25 v/$_o$ SiC$_p$/6061-T6	L	98	350	409	4.0
PLATE	T	99	345	410	4.4
20 v/$_o$ SiC$_w$/6061-DGT6 TUBE	L	108	374	520	2.7

Legend: E = Young's Modulus; σ_y = 0.2% Flow Stress; σ_{uts} = Ultimate Tensile Strength; % Elong = Percent Elongation
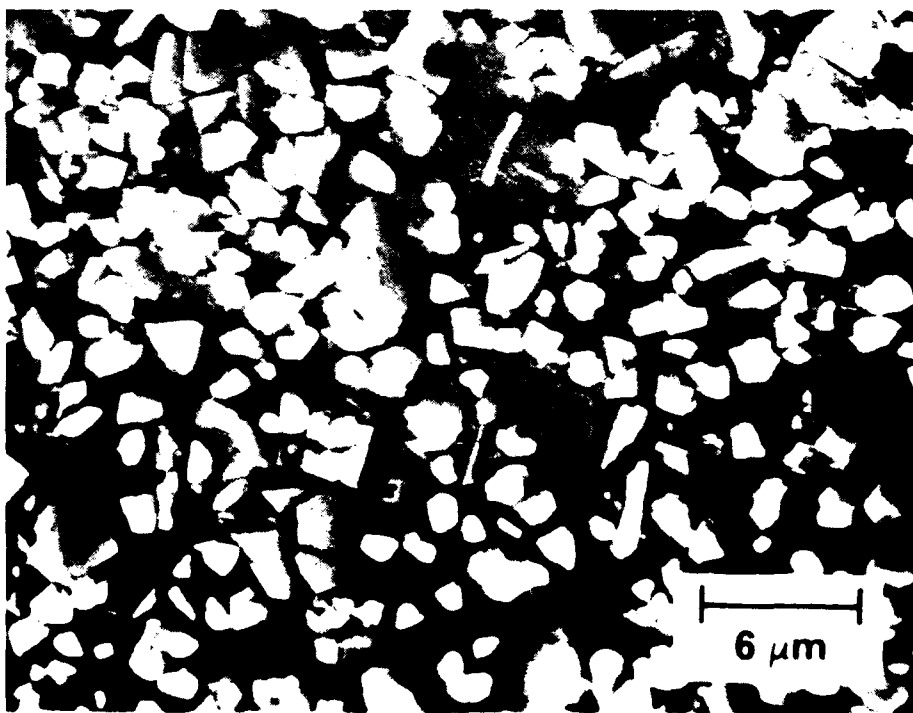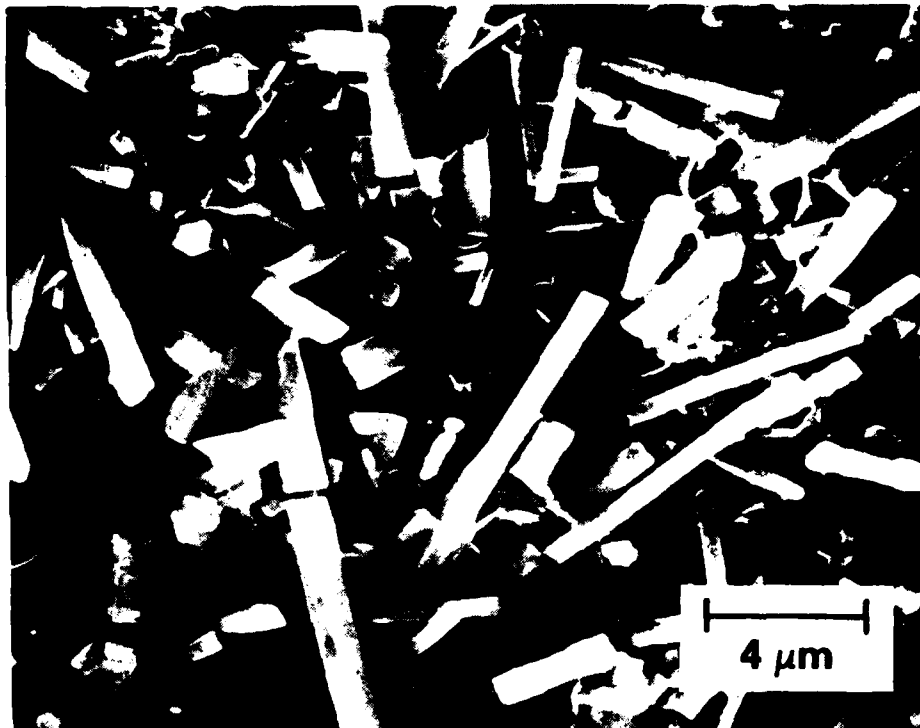
Fig. 1 - Microstructure of SiC/6061 metal matrix composites: a) whisker rein-
forced materials and b) particulate reinforced material.

RESULTS AND DISCUSSION

The effect of notch acuity on the apparent plane strain fracture toughness has been studied by a number of authors.[15-18] The general trend has been to fit the apparent plane strain fracture toughness, $K_{Ic}(\rho)$, data to a discontinuous function of the square root of notch root radius, $\sqrt{\rho}$ of the form:

$$K_{Ic}(\rho) = A \sqrt{\rho} \qquad \rho > \rho_0 \qquad\qquad 1(a)$$

$$K_{Ic}(\rho) = K_{Ic} \qquad \rho < \rho_0 \qquad\qquad 1(b)$$

where A and ρ_0 are constants. The linear portion of the function extrapolates through the origin. A close examination of the available data shows, however, that the data usually exhibits a smooth transition between the regions defined by Eq. 1 a) and 1 b) rather than a discontinuity. Furthermore, a least squares fit to the linear data often demonstrates a positive intercept. This positive intercept has been interpreted as being related to interactions between the crack and the microstructure.[15]

The preceeding method, in conjunction with crack opening displacement measurements have been used to study the effect of notch acuity on the plane strain fracture toughness of 6.26 mm thick SiC/Al MMC plate.[12] The data showed that SiC/Al composite produced using particulate SiC as the reinforcement exhibited significant values of the intercept, A, when a least squares fit was performed, whereas the intercept was close to zero for whisker reinforced material.

An alternate analysis of the data can be performed using the function:

$$K_{Ic}(\rho) = K_{Ic} \frac{(1 + \rho/2\ell)^{3/2}}{(1 + \rho/\ell)} \qquad\qquad (2)$$

derived to analyze crack tip blunting mechanisms in polymers (e.g. PMMA).[19] In Eq. (2), ℓ is a characteristic length in front of the crack tip and $\ell < \rho_0$.

Equation (2) passes through a minumum at $\rho = \ell$ and approximates

$$K_{Ic}(\rho) = \frac{K_{Ic}}{2} \left(\frac{\rho}{2\ell}\right)^{1/2} \qquad \text{for } \rho \gg \ell \qquad\qquad (3)$$

Equation (3) has the same form of Eq. 1(a).

Figures 2 through 4 show the available data on SiC/Al and the fit with Eq. (2). As can be seen the agreement between Eq. (2) and the data is very good over the entire range of measurements.
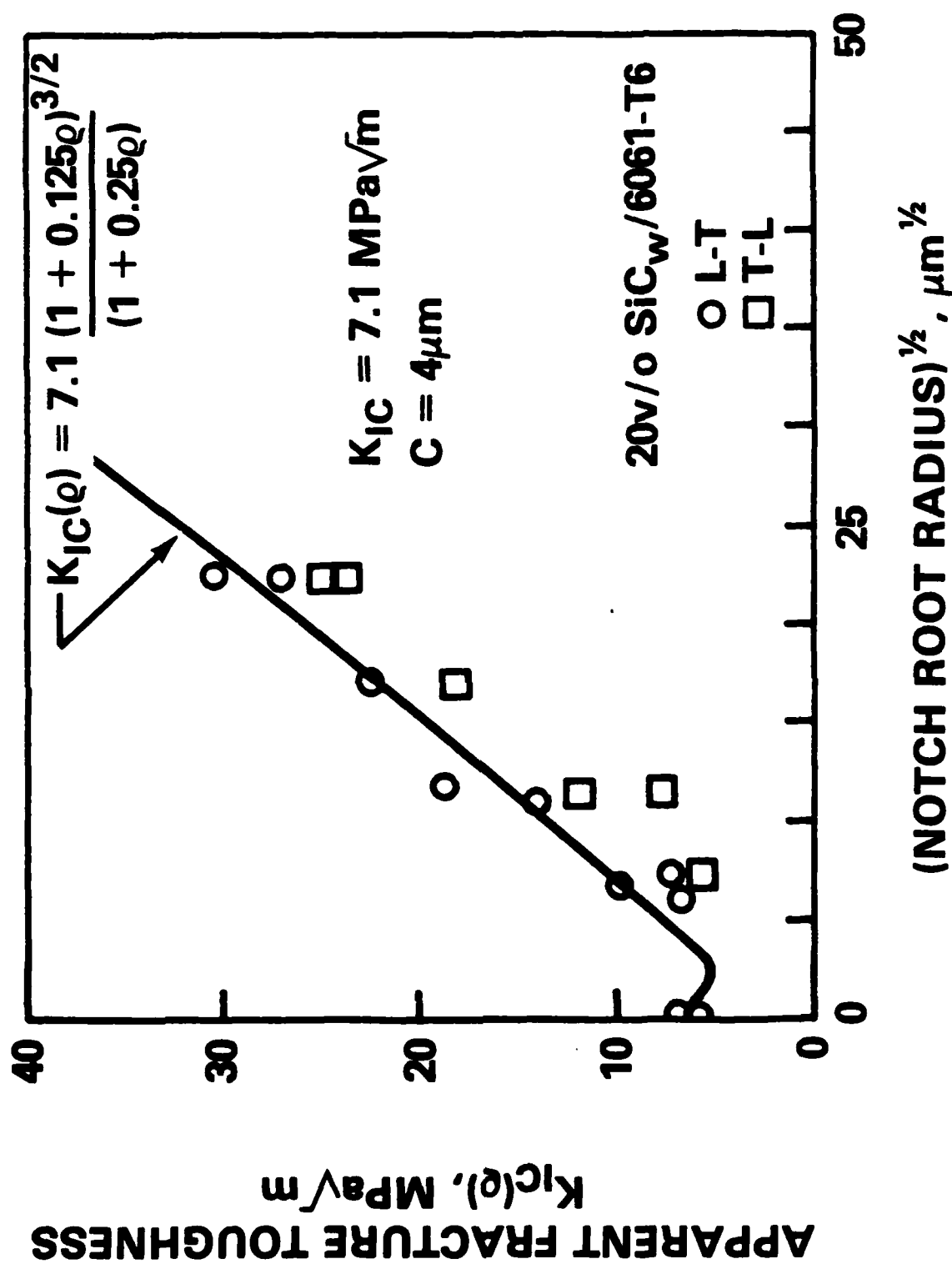
$$K_{IC}(\varrho) = 7.1 \frac{(1 + 0.125\varrho)^{3/2}}{(1 + 0.25\varrho)}$$

$K_{IC} = 7.1$ MPa$\sqrt{m}$

$C = 4\mu m$

20v/o SiC$_w$/6061-T6

O L-T
□ T-L

(NOTCH ROOT RADIUS)$^{1/2}$, $\mu m^{1/2}$

APPARENT FRACTURE TOUGHNESS $K_{IC}(\varrho)$, MPa$\sqrt{m}$

Fig. 2 - The effect of notch root radius on the apparent fracture toughness of whisker reinforced SiC/6061 Al MMC from 6.35 mm thick plate.

$K_{IC} = 12.1$ MPa$\sqrt{m}$

$C = 45.4$ μm

$K_{IC}^{(\varrho)} = 12.1 \dfrac{(1 + \varrho/90.8)^{3/2}}{(1 + \varrho/45.4)}$

(NOTCH ROOT RADIUS)$^{1/2}$, μm$^{1/2}$

APPARENT FRACTURE TOUGHNESS
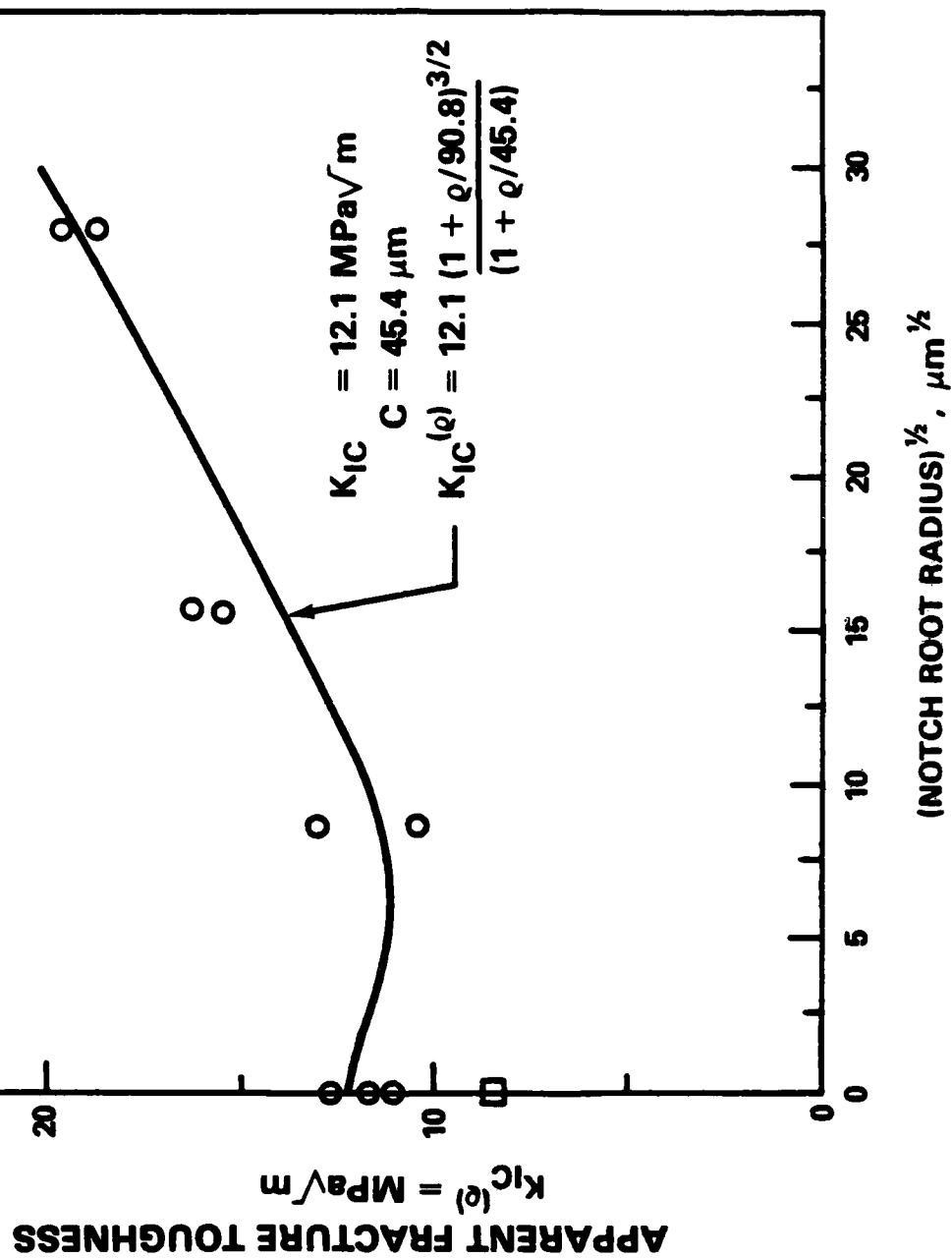$K_{IC}^{(\varrho)} = $ MPa$\sqrt{m}$

Fig. 3 – The effect of notch root radius on the apparent fracture toughness of whisker reinforced SiC/6061 Al MMC from a thick walled extruded tube.
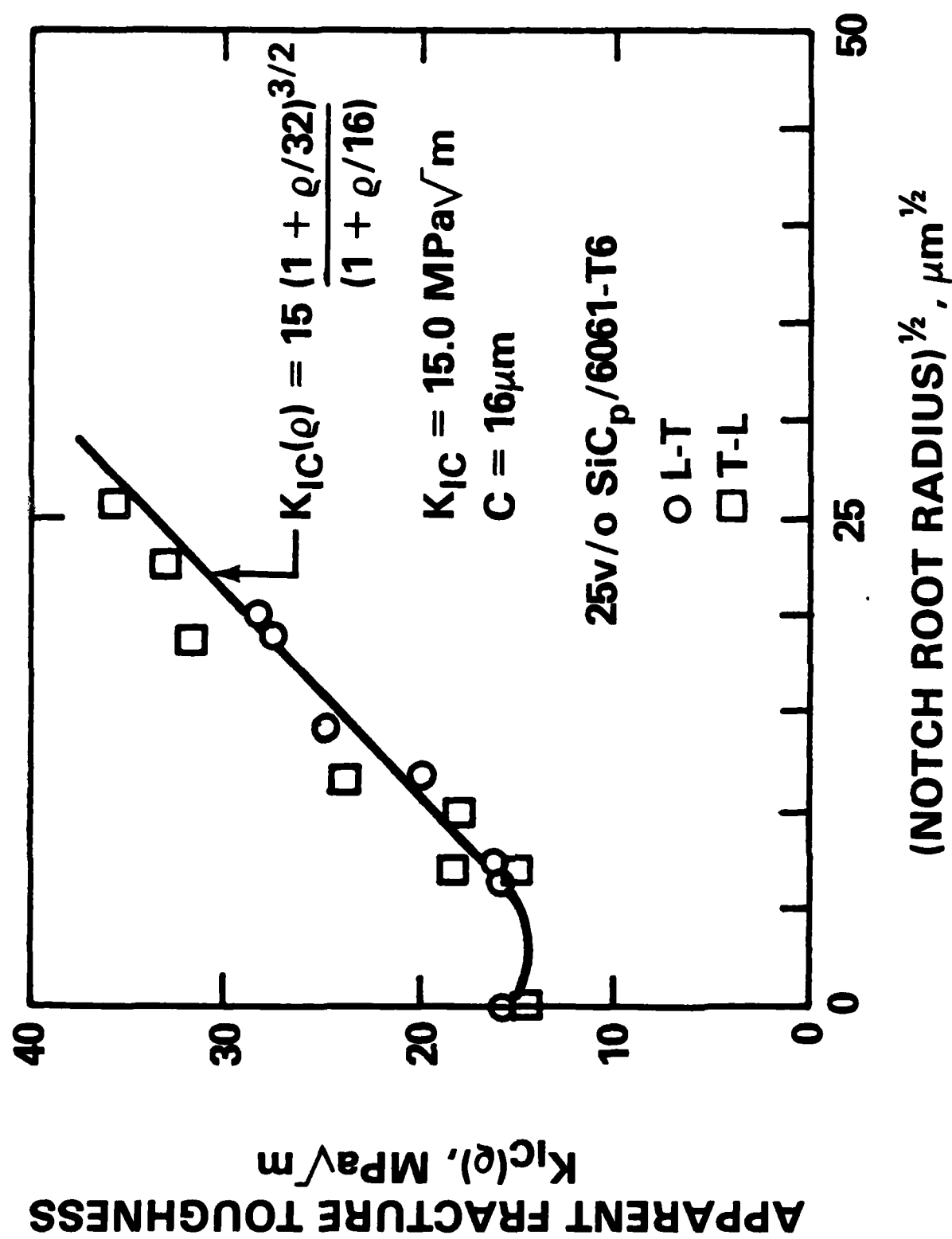
Fig. 4 - The effect of notch root radius on the apparent fracture toughness of particulate reinforced SiC/6061 Al MMC from 6.35 mm thick plate.

The use of Eq. (2) has the very practical advantage of providing a method of extracting K_{IC} from measurements on samples with finite root radii. Since Eq. (2) is a two parameter relationship, two specimens with different root radii provide sufficient information to extract K_{IC} from non-precracked tests. The model described by Eq.'s 1 a) and b) cannot easily achieve this result because accurate control of the root radius at small radii is difficult to achieve in practice. Agreement with Eq. (2) fails at high ρ since the crack does not always initiate at 90° to the direction of load. In the present study, this deviation from linearity has been observed for $\rho > 300$ μm.

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